Response to Editor

Many thanks for handling our paper and the comments. We revised the article according your comments.

(i) Referee 1 raises a good question about why you have not shown results for a larger set of warmings. I might correspondingly ask why you have chosen to show composites in figure 5 which are identical to those already presented in Kodera (2006) when actually a further 10 years or so of data is now available and could be exploited.

The reason why we do not make a new composite analysis in the present paper is that we think we first need to better understand the relationship between the tropical and extratropical circulation within the stratosphere during the SSW events. It should be noted that major SSWs do not necessarily produce large impact on the tropical stratosphere. For producing a tropical impact, meridional extent of SSW is important, but this has not been well studied. Therefore, we need first to study the mechanism creating a different temporal and meridional characteristics of the SSW. Figure A1 shows zonal-mean zonal wind at 10hPa, 60°N (top), eddy heat flux at 100hPa averaged over 45-75°N latitudes (middle), and anomalous zonal mean pressure-coordinate vertical velocity (bottom) for the winters of 2007-2010. Major SSW occurred every year for these consecutive boreal winters. Therefore, zonal wind at 10hPa, 60N becomes easterly in every cases. However, the deceleration of zonal winds during the SSWs of 2009 and 2010 are largest among the SSWs as described in the text. Also, tropical cooling associated with these SSWs are prominent. Currently, we are making a separate investigation on this problem (Kodera et al., personal communication given at the 2015 AMS general assembly). We are, therefore, planning to make a composite analysis after having obtained a knowledge to newly define the events and the key dates, rather than repeating the same analysis with just some additional events in the present paper.

(ii) Referee 2 is unconvinced by the relationships between physical variables that the paper claims to identify, is concerned about statistical significance and is skeptical of your claim that 'convective overshooting clouds show a direct relationship to lower stratospheric upwelling at around 70-50 hPa'. (Note that when this referee refers to CALIPSO results in Fig 2 I think they mean CALIOP results in Fig 3.)

A reason why the referee 2 questions the direct relationship between the stratospheric upwelling and the clouds may be that he or she cannot find any clouds above 18 km in Fig. 3. It should be noted that variables shown in Fig. 3 are zonally averaged quantities. The deep convective clouds are formed over limited areas such as over continents and warm ocean near the lands. Therefore, it is natural that one cannot see their presence in Fig. 3. Changes in the cloud frequency over African continent during the SSW event in 2007 by Eguchi and Kodera (2010) is reproduced in Fig. A2. One can see an increase in the cloud frequency above 18km after the onset of the SSW. It should be noted that this is not only due to a condensation of the environmental water vapor, but the water is vertically transported due to increased deep convection as discussed in Eguchi and Kodera (2010) .

Formation of clouds above tropopause with enhanced Brewer-Dobson circulation is also seen in the analysis of Li et al. (2013).

I have looked through the paper carefully myself and make the additional comments below. Again please can you address these as far as possible in your revision.

p2 l26: ‘how stability affects anvil cloud top height’ — stability at what level? lower stratosphere?

The phrase has been modified as "stability near—tropopause".

p2 l30: Eguchu et al (2014) — please update reference (in reference list) to give details of publication in ACP (not ACPD).

Reference modified as "Eguchi, N., K. Kodera, and T. Nasuno (2015), A global non-hydrostatic model study of a downward coupling through the tropical tropopause layer during a stratospheric sudden warming, Atmos. Chem. Phys., 15, 297–304, 2015."

p3 l5: ‘decreases’

Corrected

p3 l13: ‘statistical analysis’ > ‘composite analysis’

Corrected

p3 l15: ‘exceptionary’ > ‘exceptionally’

Corrected

p3 l21: ‘latitude of the wave breaking’ — expand a little, e.g. ‘latitude of the associated planetary wave breaking’

Modified as suggested: "latitude of the associated planetary wave breaking".

p3 l25: ‘and winds’ — including vertical velocity?

Yes. The phrase is modified as " winds including vertical velocity".

p4 l22: ‘An enhanced’

Corrected

p4 l30: ‘In the tropics an increase in COV is synchronous with the stratospheric upwelling’ — personally I found it pretty difficult to see this (and therefore I have some sympathy with Referee 2) — anything you can say to support this statement would be helpful. Also the vertical velocity is noisy — how much of this structure is believable?

Gravity wave like structure is seen in the horizontal map of vertical velocity. So, the noisy structure may be natural.

To indicate the difference, the following sentence is added in the text (p.6 l8-10), "The difference in the characteristics in the temporal variation in COV and OLR relative to the vertical velocity at 50 hPa becomes also apparent in the vertical structure of the correlation coefficient in the following."

p5 l18-30: This ‘statistical test’ seems very ad hoc to me — in particular the second and third inequalities in (1) seem to be based on not much more than guesswork. Again bearing in mind Referee 2’s comments, I think it would be better based your arguments on e.g. identifying robust and coherent spatial patterns rather than on what seem rather spurious measures of statistical significance.

According to the comment, the following sentences have been removed from the text. "If there is no physical relationship among the variables, such conditions are satisfied in $(1/2)^3$ of the cases by chance. In the present case, this occurred during two winters, so that the probability that this happened by chance is $(1/2)^6$; i.e., only about 1.5% of the cases. If the COV, DC, and OLR were strongly correlated to each other, correlation coefficients would be similar, which makes the condition (1) less satisfied."

Instead, the following sentence has been added (p.6 l1). " Such relationship is satisfied in the correlation analysis presented in Fig. 2." Also, the following sentences has been added (p.6 l4-10) to indicate the similarity of the spatial structure between the results of regression study by Li and Thompson (2013). "The present study can also be compared with a regression study of BD circulation index by Li and Thompson (2013); Enhanced BD circulation increases clouds occurrence above the tropical tropopause, in association with a decrease of stratospheric temperature and the static stability around the tropopause. The structure of the tropical temperature and stability change associated with the COV is consistent with a variation associated with a strengthening of the BD circulation. Formation of the clouds above the tropopause is also consistent with the correlation of COV with upwelling above 100 hPa."

p7 l17: ‘COV clouds can penetrate above the tropopause’ — don’t they penetrate above the tropopause by definition?

Yes, the definition of COV is the cloud penetrating higher than zero buoyancy level. Usually it is found around the TTL-tropopause level.

The sentence has been modified as follows. "COV clouds penetrate above the tropopause".

p8 l13: ‘better’ > ‘stronger’

Corrected

Figure 3 caption: second (c) should be (d). It would be easier to interpret this figure if the vertical axis for (b) was the same as for (a) and (c).

Corrected to (d).

The log-pressure coordinate is added to the vertical axis for (b).

Figure 4 caption is not at all clear — you don’t properly identify the lower panels in each sub-figure as showing COV.

The caption is remade as follows. Figure 4. (a, c, e, g): seven-day mean OLR (color shadings) with velocity potential at 925 hPa (contours of –6, and -8×10^6 m^2 s^{-1}). (b, d, f, h): seven-day average of the number of COV in each 2.5° lat/lon grid box. (a,b) and (c,d) are seven-day period before (i) and after (ii) the onset of the event in January 2009. (e,f) and (g, h) are the same as (a,b) and (c,d), except for the event in January 2010.

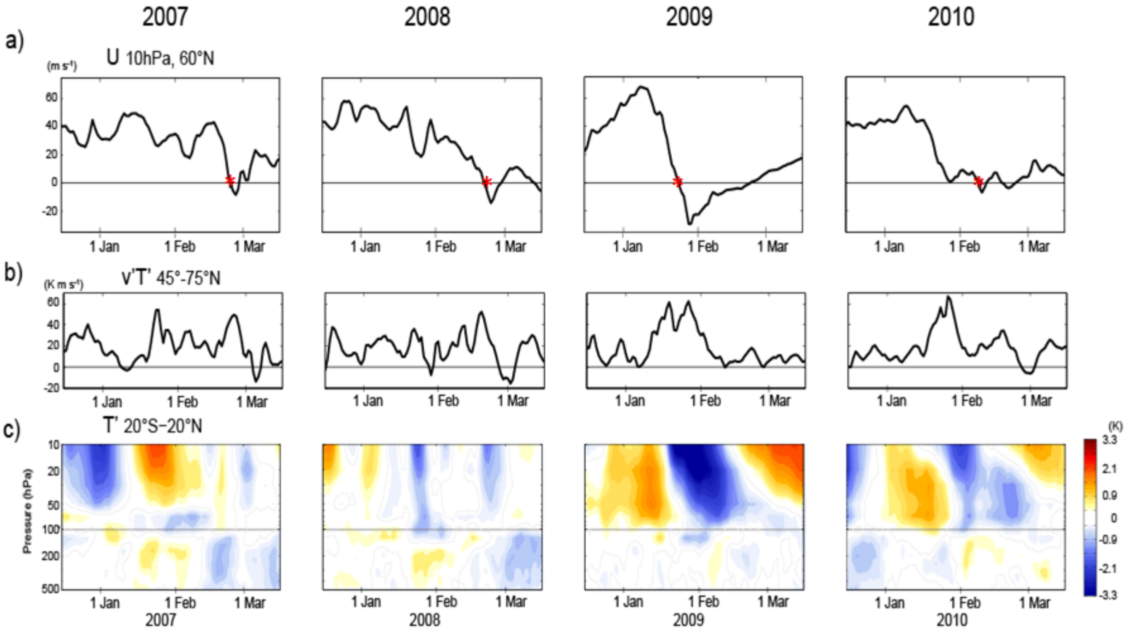

Fig. Ed_A1. a) Zonal-mean zonal wind at 10hPa, 60°N, b) eddy heat flux at 100hPa averaged over 45-75°N latitudes, c) height-time section of anomalous tropical (20°S-20°N) temperature, during 4 consecutive winters 2007- 2010 from 16 December to 16 March. Asterisks in (a) indicate central date of the major warming (from Kodera et al., 2015)

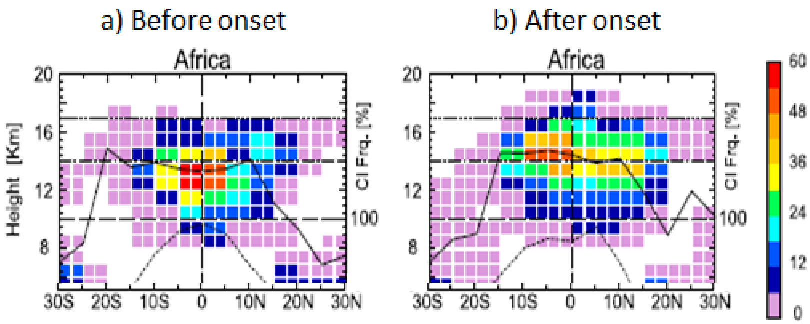

Fig Ed_A2. Latitude-pressure sections of cirrus cloud frequency [%] obtained from CALIOP over African sector (10°E–40°E) before and after the SSW onset: (a) 6- 15 and (b) 16-25 September 2007. (from Eguchi and Kodera, 2010)

Response to Referee #1

Thank you for the reading our article and the comments.

My opinion of this paper has not changed following revision. While the influence of stratospheric sudden warmings (SSW) on tropical convection is an extremely interesting problem, I am not convinced by the analyses in this paper of robust relationships during the two events in 2009 and 2010. The key point of this paper is that 'influence penetrates downward into the troposphere through a change in cloud formation', but I am unconvinced by the relationships between vertical velocity, temperature and cloud statistics shown in the paper. If the deepest convective clouds are an important physical intermediary, then I would expect some clear causal relationships between stratospheric circulation/temperature, deepest overshooting convection and OLR (with appropriate time lags), but this is not demonstrated in these results. The statistical significance of the individual correlations in Fig. 2 was not addressed in revision, but rather the 'physical consistency' among the separate calculations was discussed. It is still unclear to me if any of the results in Fig. 2 are statistically significant. I am still confused regarding the important information in Fig. 4. The addition of the composited SSW results from Kodera (2006) in Fig. 5 is a useful comparison for these case studies, but I am unconvinced that the deepest overshooting convection (COV) somehow plays a role in the coupling (Fig. 1 and Fig. 4 are not convincing on this point; the CALIPSO results in Fig. 2 do not show any clouds above 18 km). The results do not clearly and simply demonstrate that the 'convective overshooting clouds show a direct relationship to lower stratospheric upwelling at around 70-50 hPa'. Overall I think the results are suggestive at best, but the key, novel points of the paper are not proven convincingly, and I do not recommend this paper for publication.

The reviewer stated that he or she cannot see any clouds above 18 km in CALIOP data in Fig. 3. This may be a reason why the reviewer questions the direct linkage between the stratospheric upwelling and clouds. The reason why clouds do not manifest above 18 km is that what is shown in Fig. 3 are zonally averaged quantities. Deep penetrative convections occur rather in limited areas of the globe. Therefore, it is natural that it becomes too small to be seen in the zonal mean field. As an example, cloud frequency change over African continent during the SSW event in 2007 (Eguchi and Kodera, 2010) is reproduced in Fig. R1_A1. One can clearly see the increase of clouds above 18km after the onset of the SSW. It should be noted that this is not only due to a condensation of the environmental water vapor, but the water is transported by enhanced deep convective activity as discussed in their paper.

A SSW event in a global cloud resolving model (Eguchi et al., 2014) also showed an increase of diabatic heating above 18 km in association with enhanced deep convective activity. Formation of clouds above the tropopause with enhanced Brewer-Dobson (BD) circulation is also seen in the analysis of Li et al. (2013). Figure R1_A2 compares the present correlations of COV in Fig. 2 with their regression analysis with BD circulation index (extratropical heat flux at 100 hPa). Enhanced BD circulation decreases the stratospheric temperature and the static stability around the tropopause, to which associates an increase of clouds above the tropopause. Temperature and stability change associated with the COV is consistent with a variation associated with a strengthening of the BD circulation. Also the formation of the clouds above the tropopause is consistent with the correlation of COV with the tropical upwelling above 100 hPa. To indicate that the correlation patterns in Fig. 2 carry useful information, the following sentences have been added to the text (p.6, l4-10).

" The present correlations study can also be compared with a regression study of BD circulation index by Li and Thompson (2013); enhanced BD circulation increases clouds above the tropical tropopause, in association with a decrease of stratospheric temperature and the static stability around the tropopause. Structure of tropical temperature and stability change associated with the COV is consistent with a variation associated with a strengthening of the BD circulation. Formation of the clouds above the tropopause is also consistent with the correlation of COV with upwelling above 100 hPa."

The reviewer emphasis a necessity of the statistical significance of the individual correlations. However, at the present stage of the research, finding of 'physical consistency' is essential. This is because, to make a meaningful statistical analysis, one needs to identify the process at first.

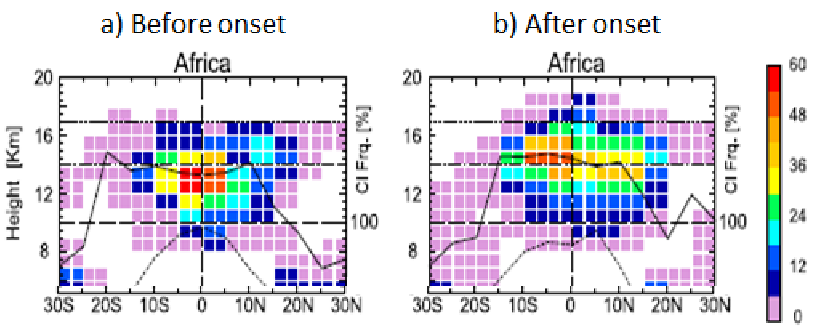

Fig. R1_A1. Latitude-pressure sections of cirrus cloud frequency [%] obtained from CALIOP over African sector (10°E−40°E) before and after the SSW onset: (a) 6- 15 and (b) 16-25 September 2007. (from Eguchi and Kodera, 2010)

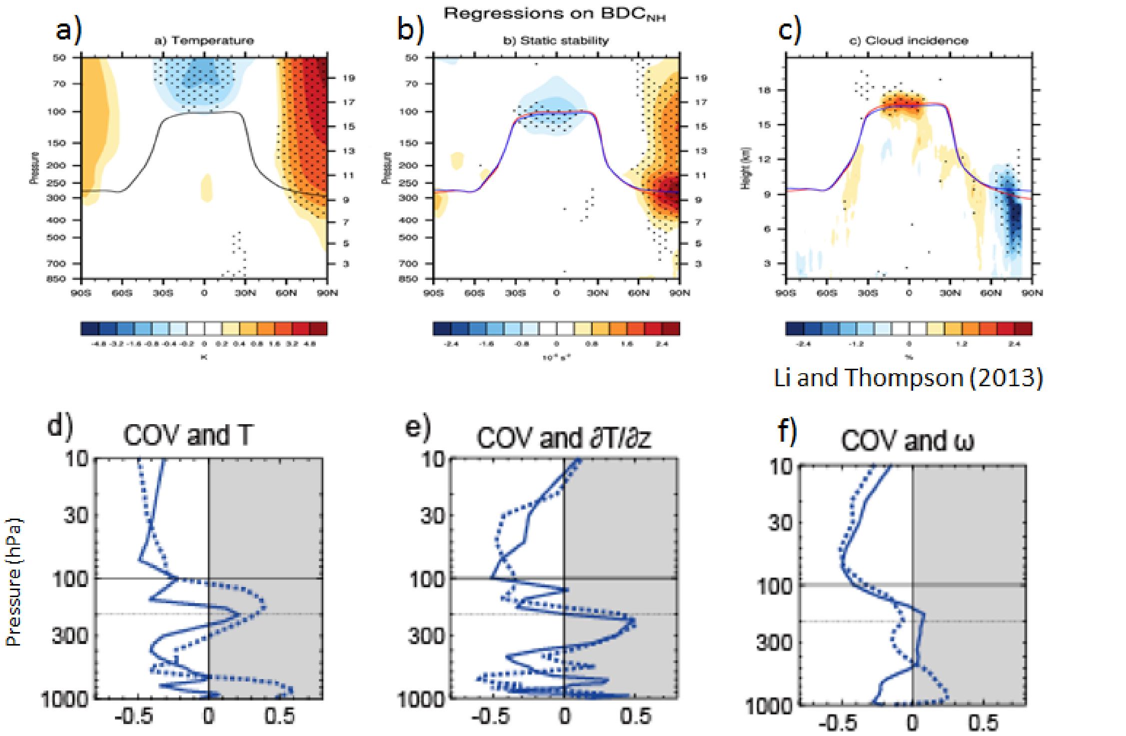

Figure R1_A2 (top) Regression analysis between BD circulation index (extratropical heat flux at 100 hPa) and a) air temperature, b) static stability, and c) Cloud incidence, by Li and Thompson (2013). (bottom) Present correlation analysis between COV and d) air temperature, e) vertical temperature gradient, and f) pressure coordinate vertical velocity.

Response to Referee #2

Many thanks for your interests and comments on our paper. We modified the article according your comments.

This paper discusses the changes in cloud properties as observed by satellite data following two recent stratospheric sudden warmings. Sudden warmings lead to more upwelling over the next week, which in turn leads to more clouds in the TTL. This is an interesting subject and the work is novel. The authors' points are very clearly conveyed, and I appreciate the extended discussion of robustness. I am still somewhat bothered that the authors focus only on 2 of the handful of SSW that have occurred over the period for which their data sources are available, and thus the significance test they include is not entirely convincing. The authors should include this additional analysis.

General Comments:

1. I still would appreciate a more detailed discussion of the other SSW events for which data is available but which aren't analyzed in this paper. Since 2010 there have been (at least) three SSW. Repeating the authors' analysis for these would be very interesting. Even if the results were different than for these two, it would be enlightening. If the relationship they find isn't present in these other events, the authors need to explain why not (e.g. the lower stratospheric tropical upwelling is weak or nonexistent, and thus the feedbacks never are able to develop), or I have trouble believing their results and the significance "test". This analysis doesn't even need to be in the actual body of the paper, but it should be in supplemental work at the very least.

Response

The reviewer wonder why we have limited our analysis on only two SSWs. This is because the SSWs in 2009 and 2010 are exceptionally large and well localized in time. Figure A1 depicts how the SSWs in 2009 and 2010 are different from other SSWs such as those in 2008 and 2007. Large and simple structure of the temporal variation of the forcing (eddy heat flux) and the response (zonal wind) of the SSWs of 2009 and 2010 permit us to investigate without taking an averaging. The following sentence has been added (p.3 l19-23) to explain the reason of our choice.

" These SSWs are not only large, but also localized in time unlike other SSWs. Large and simple structure of the temporal variation of the forcing (eddy heat flux) and the response (stratospheric zonal wind) of 2009 and 2010 SSWs permit us to investigate a detailed feature of the circulation change."

The reviewer stated that there have been (at least) three SSW since 2010. However, there is only one major SSW in January 2013 since 2010. The date when the zonal wind at 10hPa, 60N becomes easterly (central date) is indicated by an asterisk in Fig. A1. This event is sufficiently large, but the decrease of the polar night jet occurs rather gradually by intermittent wave forcings. The breakdown of polar vortex occurs with the third wave enhancement, while the tropical cooling starts already at the second enhancement. In the case of such complex SSW, it is not easy to see the detailed relationship between the stratosphere and the troposphere. We can, however, recognize an intensification of convective activity in the SH following a cooling in the tropical stratosphere, consistent with the present results.

Minor comments:

I appreciate the discussion of the MJO at the end. Note that the MJO evolution for the 2009 /2010 case is consistent with that found by Garfinkel et al 2012 and Liu et al 2014

Garfinkel, C. I., Feldstein, S. B., Waugh, D. W., Yoo, C., & Lee, S. (2012). Observed connection between stratospheric sudden warmings and the Madden - Julian Oscillation. Geophysical Research Letters, 39(18).

Liu, C., Tian, B., Li, K. F., Manney, G. L., Livesey, N. J., Yung, Y. L., & Waliser, D. E. (2014). Northern Hemisphere mid - winter vortex - displacement and vortex - split stratospheric sudden warmings: Influence of the Madden - Julian Oscillation and Quasi - Biennial Oscillation. Journal of Geophysical Research: Atmospheres, 119(22), 12-599.

According the comment, the following sentence has been added in the text (p9 l11-11).

"It is reported that the occurrence of the SSW is related with the phase of the MJO (Garfinkel et al, 2012: Liu et al 2014)."

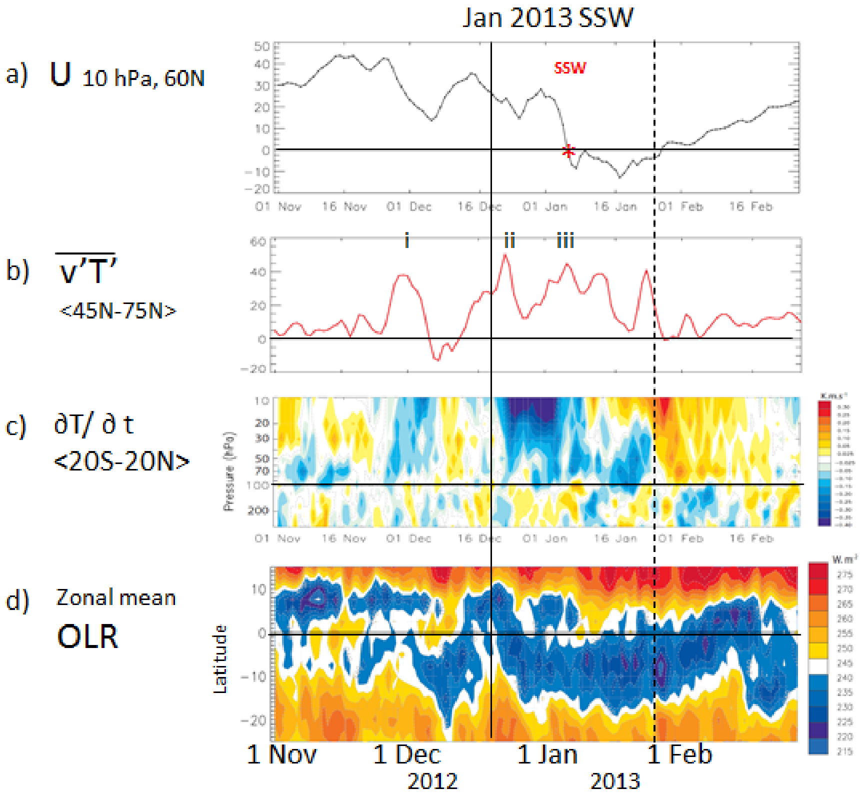

Fig. R2_A1 a) Zonal-mean zonal wind at 60°N, 10 hPa. b) Eddy heat flux at 100 hPa averaged over 45°N-75°N. c) Tropical (20°S-20°N) temperature tendency . c) Zonal mean OLR. Period of analysis from 1 Nov. 2012 to 28 Feb. 2013. Asterisk denote the central date of the SSW.

Anonymous Referee #3

Many thanks for your comments.

I am now generally happy that the authors have responded to most of my comments. I recommended publish after a minor revision.

The only remaining comments I have are:
1) P8: The authors provide possible physical process explaining the increases of COV might be due to the decreases of static stability around the tropopause. The relationship between clouds in TTL, vertical motion, and static stability has been noted in Li et al, JGR, see their Fig. 9a.

Li, Y. D. W. J. Thompson, G. L. Stephens and S. Bony, 2014: A global survey of the instantaneous linkages between cloud vertical structure and large-scale climate. J. Geophys. Res., 119, 3770–3792.

Thanks for providing the reference. In fact, their Fig. 9a of height-latitude section (regression of cloud incidence on static stability) has two centers. It is possible to attribute the cloud incidence change around 100 Pa to the BD circulation in Fig. 9a of Li et al. but there is another center in the upper TTL (150 hPa). The second center in the TTL occupies only narrow region around the equator (10°S-10°N), which may be attributable to the influence of equatorial planetary waves. The impact of BD circulation on cloud incidence and static stability is shown in one of their companion paper in Fig. 4 (Li and Thompson, 2013). So, here we referred rather Li and Thompson (2013).

2) P8 line 21: “warming” would that be “cooling”?

The word "warming" is correct. To avoid an ambiguity, we rephrased as follows (p.8 l27-29).

Our previous numerical experiment also shows that "when local cooling occurs near the tropopause, upwelling enhances accompanying a warming in the lower TTL and the upper troposphere".

The role of convective overshooting clouds in tropical stratosphere–troposphere dynamical coupling

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Abstract

This paper investigates the role of deep convection and overshooting convective clouds in stratosphere–troposphere dynamical coupling in the tropics during two large major stratospheric sudden warming events in January 2009 and January 2010. During both events, convective activity and precipitation increased in the equatorial Southern Hemisphere as a result of a strengthening of the Brewer–Dobson circulation induced by enhanced stratospheric planetary wave activity. Correlation coefficients between variables related to the convective activity and the vertical velocity were calculated to identify the processes connecting stratospheric variability to the troposphere. Convective overshooting clouds showed a direct relationship to lower stratospheric upwelling at around 70–50 hPa. As the tropospheric circulation change lags behind that of the stratosphere, outgoing longwave radiation shows almost no simultaneous correlation with the stratospheric upwelling. This result suggests that the stratospheric circulation change first penetrates into the troposphere through the modulation of deep convective activity.

1 Introduction

Weather forecasting in tropical regions is challenging due to the unstable nature of the atmosphere there and its sensitivity to various extratropical disturbances. The impact of the extratropical circulation on the tropics, such as the lateral propagation of tropospheric Rossby waves, has been studied previously (e.g., Kiladis and Weickmann, 1992; Funatsu and Waugh, 2008). The influence from above (i.e., from the stratosphere) is generally neglected, but under certain circumstances, such as during a sudden stratospheric warming (SSW) event, stratospheric meridional circulation change can modify convective activity as will be shown later.

Early satellite measurements showed that enhanced poleward eddy heat fluxes in the extratropical stratosphere induce tropical cooling through changes in the mean meridional circulation (Fritz and Soules, 1970; Plumb and Eluszkiewicz, 1999; Randel et al., 2002). It is generally believed that such changes in the stratosphere do not affect the troposphere, due to the difference in air density between the two. Indeed, tropical temperature change induced by the intraseasonal mean meridional circulation is apparent only in the layer around 70 hPa and above (Ueyama et al., 2013).

However, this does not imply that the stratospheric meridional circulation has no impact on the atmosphere below the 70hPa level. A possible impact of stratospheric meridional circulation on cumulus heating has been suggested by Thuburn and Craig (2000) in a simplified general circulation model experiment. Stratospheric upwelling effects on tropical convection is also confirmed by a more realistic general circulation model forecast study (Kodera et al., 2011a). These models make use of cumulus parameterization to account for the effect of convection into large scale circulation. Therefore, model sensitivity should be dependent on the parameterization used.

Stratospheric effect on tropical convection is also found in non-hydrostatic models that treat the convection explicitly. Although it is not fully understood yet how stability near-tropopaus influences anvil cloud-top height, Chae and Sherwood (2010) showed with observational data and a regional non-hydrostatic model experiment that the variation of static stability near the tropopause due to a change in the stratospheric upwelling, influences cloud height even if the cloud height peaks only near 12 km (or 200hPa). Using a global non-hydrostatic model simulation, Eguchi et al. (2014) also found that increased tropical upwelling due to a SSW event reduces the static stability in the upper Tropical Tropopause layer (TTL), which leads to an increase of deep convective activity in the troposphere.

Temperature response to stratospheric upwelling becomes unclear in the region lower than the tropopause because clouds form in response to adiabatic cooling associated with upwelling. Stratospheric temperature decreases, but minimal temperature changes occur in the TTL, results in a decrease in static stability in the upper TTL (Li and Thompson, 2013). In the regions where deep convective clouds are frequent, stratospheric influence further penetrates deeper in the troposphere (Eguchi and Kodera, 2010; Kodera et al., 2011b). Once the distribution of convective clouds is modified, this effect can be amplified within the troposphere through a feedback involving water vapour transport (Eguchi and Kodera, 2007).

In a previous study composite analysis of the tropical tropospheric impact of SSW events were made for the winters from 1979 to 2001 (Kodera, 2006). Even though significant responses were found in the tropical troposphere, a problem of the composite analysis is that by averaging many different events to extract a common feature, detailed structures often become obscure. Therefore, case studies are made in the present paper on two exceptionally large events focusing on the role of overshooting and deep convective clouds in stratosphere–troposphere dynamical coupling in the tropics. The selected two largest SSW events of January 2009 and January 2010 (Harada et al., 2010; Ayarzagüena et al., 2011) have large impact on the tropical upwelling in the lower stratosphere as will be shown later. These SSWs are not only large, but also localized in time unlike other SSWs. Large and simple structure of the temporal variation of the forcing (eddy heat flux) and the response (stratospheric zonal wind) of 2009 and 2010 SSWs permit us to investigate a detailed feature of the circulation change. It should also be noted that not all major SSW events necessarily have such large tropical impacts, as this depends on the latitude of the associated planetary wave breaking (Taguchi, 2011).

2 Data

Meteorological reanalysis data from the European Centre for Medium-Range Forecasts (ECMWF) ERA interim (Dee et al., 2011) were used to analyse air temperature and winds including vertical velocity. Cloud data in the TTL, the Level 2 Cloud Layer Product (Version3-01) were obtained by Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP) aboard CALIPSO satellite (Winker et al., 2007). Outgoing longwave radiation

(OLR) data provided by NOAA (e.g., Arkin and Ardanuy, 1989) is widely used to analyse convective activity in the tropics. In this study, in addition to the OLR data with a 2.5° × 2.5° lat/lon resolution, we used the Microwave Humidity Sensor (MHS) channels 3 to 5 to detect deep convection and convective overshoots because of the scattering by icy particles in such cold precipitating clouds that causes a depression in the brightness temperatures. MHS data are obtained from NOAA18 and MetOp-A. The equatorial crossing time for these platforms is approximately 14h00 local time (LT) for NOAA18, and 21h30 LT for MetOp-A. In the present work, the original data was regridded to a regular grid with resolution of 0.25 lat x 0.25 lon. The figures show DC and COV occurrences resampled to a grid of 2.25 x 2.25 for plotting purposes.

To capture deep, precipitating clouds we used the diagnostics developed for the tropics by Hong et al. (2005), which is based on the brightness temperature differences (ΔT) measured by three channels of the MHS between: i) 183.3 ± 1 and 183.3 ± 7 GHz ($\Delta T17$); ii) 183.3 ± 1 and 183.3 ± 3 GHz ($\Delta T13$); and iii) 183.3 ± 3 and 183.3 ± 7 GHz ($\Delta T37$). Deep convective cloud (DC) and convective overshooting (COV) were discriminated according to the following criteria, in which COV refers to clouds able to penetrate into the tropopause region (Hong et al., 2005; Funatsu et al., 2012). Deep convective cloud: $\Delta T17 \geq 0$, $\Delta T13 \geq 0$, $\Delta T37 \geq 0$ K; and convective overshooting: $\Delta T17 \geq \Delta T13 \geq \Delta T37 > 0$ K.

Although these high frequencies are generally not sensitive to cirrus and anvil cirrus clouds, they will probably have difficulty distinguishing some strong anvil clouds from deep convective clouds. But fortunately, these strong anvil clouds are generally tightly connected with deep convective cloud systems (Hong et al., 2008).

The Tropical Rainfall Measuring Mission (TRMM) daily-integrated precipitation (TRMM 3B42 v7) was used to study surface precipitation (Huffman et al., 2007).

3 Results

An enhanced Brewer-Dobson (BD) circulation during a stratospheric warming event creates strong downwelling in the polar region and upwelling in the tropical stratosphere, and thus warming and cooling tendency in these respective regions. Figures 1a and 1b show the evolution of eddy heat flux at 100 hPa averaged over the extratropical Northern Hemisphere (NH; 45°N–75°N), and the latitude–time section of the zonal mean pressure coordinate vertical velocity at 50 hPa from 1 January to 11 February (the left and right panels are for 2009 and 2010, respectively). In both years, stratospheric upwelling in the tropics at the 50 hPa level strengthens following the increase in wave activity at around 16 January in 2009, and around 20 January 2010 (indicated by the solid vertical lines in the figure). In the tropics, an increase in COV is synchronous with the stratospheric upwelling (Fig. 1c). The convective activity represented by the OLR also increases in the Southern Hemisphere (SH), which can also be characterized as a southward shift of the active convective region (Fig. 1d). A delay in the response of the OLR in the SH is also noted. The difference in the characteristics in the temporal variation in COV and OLR relative to the vertical velocity at 50 hPa becomes also apparent in the vertical structure of the correlation coefficient in the following.

To study the relationship between tropospheric convective activity and the vertical velocity at different pressure levels, correlation coefficients were calculated between variables representing a convective activity (COV, DC, and OLR) and the pressure vertical velocity (ω) at each level (Fig. 2). Variables were first averaged over the tropics (25°S to 25°N) and then correlations were calculated for the 31 day period centred on the onset day (16 January for 2009 and 20 January for 2010). For convenience of comparison, the sign of the OLR was reversed (–OLR). In both winters, COV shows the highest correlation with ω in the lower stratosphere around 70–50 hPa. DC is also correlated with the stratospheric upwelling, but less so. The OLR shows little relationship with the stratospheric circulation, although it is correlated with vertical velocity in the upper troposphere.

Here, we check the physical consistency among the variables by comparing the correlation coefficients among them. It is reasonable to expect that stratospheric vertical velocity should have the strongest relationship with the occurrence of COV (i.e., convection penetrating to the stratosphere) and the weakest relationship with OLR, which is sensitive to lower clouds as well as deep convection. Therefore, the following inequalities among the correlation coefficient, r, between the lower stratospheric pressure vertical velocity, ω, should be expected:

$$r_{\omega,COV} < 0, \quad |r_{\omega,COV}| > |r_{\omega,DC}|, \quad |r_{\omega,DC}| > |r_{\omega,-OLR}|, \tag{1}$$

where $r_{\omega,COV}$, $r_{\omega,DC}$, and $r_{\omega,-OLR}$ are the correlation coefficients between ω and COV, DC, or –OLR, respectively.

Such relationship is satisfied in the correlation analysis presented in Fig. 2. This result supports our working hypothesis that lower stratospheric vertical velocity variation is coupled with the tropical convective activity.

The present study can also be compared with a regression study of BD circulation index by Li and Thompson (2013); Enhanced BD circulation increases clouds occurrence above the tropical tropopause, in association with a decrease of stratospheric temperature and the static stability around the tropopause. The structure of the tropical temperature and stability change associated with the COV is consistent with a variation associated with a strengthening of the BD circulation. Formation of the clouds above the tropopause is also consistent with the correlation of COV with upwelling above 100 hPa.

Figure 3 depicts a development of downward coupling in the equatorial summer tropics, averaged between 20°S and the equator. The temperature tendency (Fig. 3a) shows a rapid decrease in the stratosphere following the increase in the eddy heat flux in Fig. 2a, but no clear temperature signal is observed in the troposphere, which agrees with the results of previous study (Ueyama et al., 2013). Figure 3b shows altitude-time section of measured cloud frequency (optical thickness < 4) by CALIOP. Horizontal dashed lines indicate approximate height corresponding to 100 hPa pressure level (solid lines in Fig. 3a and 3c). Prior to the SSWs, thin clouds are formed near 16.6 km (or 100 hPa) around a cold point tropopause. When cooling events start, cloud forms all the depth of the TTL, indicating a development of convective activity. Pressure vertical velocity is shown as departure from the period mean normalized by a daily standard deviation at each level to visualize the large range of variation (Fig. 3c). Although vertical velocity varies in a similar manner to temperature tendency in the stratosphere, an increase in the upwelling also occurs in the troposphere following the stratospheric change. This tropospheric upwelling is associated with an increase in surface precipitation (Fig. 3d).

This result shows that the temperature tendency is a good proxy for vertical velocity in the stratosphere. However, dynamical cooling tends to be compensated by diabatic heating due to cloud formation lower than the tropopause as illustrated in Fig. 3; consequently, the temperature tendency is no longer a good indicator of the vertical velocity below 70 hPa.

Figure 4 shows the evolution of the geographical distribution of OLR and COV before (i), and after (ii) the onset of the event. The influence of the El Niño Southern Oscillation (ENSO) is evident in the OLR during period (i). In January 2009, which is a cold phase of ENSO, a well-developed region of low OLR is located over the Maritime Continent, while in January 2010, a warm phase of ENSO, it is located over the western Pacific according to the change in the equatorial Pacific sea surface temperature (SST). The velocity potential at 925 hPa (contour lines) in period (i) indicates that these convective activities are maintained by a large-scale low-level convergence. After the onset of the stratospheric event during period (ii), the low-OLR centre over the Maritime Continent or western Pacific is weakened, and multiple convective-active regions develop in the SH along 15°S. This active convective zone includes tropical cyclones and storms (names are indicated below the panel) over warm ocean sectors near Madagascar, North of Australia, and in the southwestern Pacific.

The occurrence of COV is high over the African and South American continents, but no particular enhancement is seen around the Maritime Continent–western Pacific region in period (i). This indicates the weaker dependency of COV on low-level convergence. Although the occurrence of COV increases after the onset in period (ii), no substantial change is seen in the spatial structure except that the COV distribution takes a more zonal form. The distribution of the regions with low OLR becomes increasingly similar to that of COV during period (ii). This indicates that the COV-related deep convective activity becomes important after the onset of the stratospheric event.

4 Summary and discussion

The results of our analysis of changes in tropical circulation associated with large SSWs during January 2009 and January 2010 can be summarized as follows.

Enhanced stratospheric wave activity produced a cooling in the tropical stratosphere through a strengthening of the BD circulation. This influence penetrated downward into the troposphere through a change in the cloud formation. Among the variables representing different convective activity, COV shows the highest correlation with the lower stratospheric vertical velocity. This result is reasonable because the COV clouds penetrate above the tropopause and interact directly with the stratospheric circulation. The reason of low correlation of the OLR with stratospheric upwelling originates from the fact that the tropospheric variation lags by about a week (Fig. 1).

The results obtained from the present two SSW events are consistent with the earlier results from an independent composite analysis of the NH winters for a period of 1979 to 2001.

Figure 5a shows the results of the above mentioned composite analysis. Twelve SSW events of which maximum deceleration of the polar night jet (average 50°N-70°°N) at 10hPa exceeds 2ms^{-1}/day with a smoothed data are selected (see detail in Kodera 2006). The key day is defined as the day of the largest deceleration. Student-*t* values corresponding to a 95% significance level for one- and two-sided tests are 1.8 and 2.2, respectively. Following a deceleration of the polar night jet, statistically significant increase in the upwelling occurs in the tropical stratosphere around day 2, and in the tropospheric equatorial SH around day 4 to 11.

Two SSW events in the present study are juxtaposed below in Fig. 5b. The top panel shows the zonal-mean zonal wind tendency of winters 2009 and 2010 similar to Fig 5a-top panel. The tropical vertical pressure velocity in the SH (20°S-Eq) is presented in a similar way as the composite analysis by choosing the day of the maximum deceleration as the time origin. We can see that the upwelling in the tropical SH increases in the upper troposphere around day 4 to day 11 similarly to the composite mean (rectangles in Fig. 5). It is clear that by adding the present two cases, statistical significance further increases. Therefore, we consider that the relationship between the enhancement of tropical convection and SSW shown in the present study is robust enough.

To get an insight into a possible mechanism of connection between the stratospheric and tropospheric variability, we also calculated correlations between the temperature or vertical temperature gradient (or static stability) at each level, and COV or -OLR (Fig. 2 bottom). COV shows stronger relationship around the tropopause with vertical temperature gradient (Fig. 2e) than temperature itself (Fig. 2d). This means that COV is sensitive to the stability around the tropopause region (100 hPa), while OLR is related with the static stability in the upper troposphere (Fig. 2f). This result indicates that COV increases due to a decrease of static stability around the tropopause induced by a cooling in the lower stratosphere associated with the SSW, consistent with the results of Kuang and Bretherton (2004) and Chae and Sherwood (2010). Our previous numerical experiment also shows that when local cooling occurs near the tropopause, upwelling enhances accompanying a warming in the lower TTL and the upper troposphere (see Figure 4 of Kodera et al., 2011a). A global non-hydrostatic model study (Eguchi et al., 2014) also confirmed the relationship suggested in the present result. Therefore, we consider that although the cooling effect by stratospheric upwelling is limited in the stratosphere, its effect can further penetrate below through changes in COV and deep convective activity.

Changes were also noted in the spatial distribution of the convective activity following the stratospheric event (Figure 4). When stratospheric upwelling was suppressed before the onset of the event (period i), convection tended to cluster around the equatorial Maritime Continent or western Pacific region depending on the phase of ENSO. When the stratospheric upwelling increased (period ii), convection expanded over a wide range of longitudes in the tropical summer hemisphere. In other words, tropical circulation changed from a more Walker like (east–west) configuration to a more Hadley (north–south) type.

The Madden–Julian Oscillation (MJO) (Madden and Julian, 1994) has a significant influence on tropical convective activity. It is reported that the occurrence of the SSW is related with the phase of the MJO (Garfinkel et al, 2012: Liu et al 2014). One would ask whether or not the present phenomenon is associated with the MJO. The features of the MJO in January 2009 and 2010 differed significantly as can be seen in Figure 6. A convective centre remained stationary over the Maritime Continent prior to the onset of the 2009 stratospheric event, after which an eastward propagation was initiated from the Indian Ocean. In contrast, an eastward propagating convective centre became almost stationary over the western Pacific after the onset in January 2010. In spite of the differences in the MJO in January 2009 and 2010, circulation changes related to the stratospheric events showed similar features during both winters, suggesting that the present phenomenon is independent of the MJO.

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Figure captions

Figure 1. a) Time series of the eddy heat flux at 100 hPa averaged over 45°N–75°N [K ms^{-1}]. b) Zonal mean pressure coordinate vertical velocity at 50 hPa [Pa s^{-1}]. c) Number of convective overshootings per day at each latitude. d) Zonal mean OLR [W m^{-2}]. Variables are displayed from 1 January to 11 February. Left- and right-hand panels are for 2009 and 2010, respectively. Vertical velocity and OLR data are smoothed by a three-day running mean.

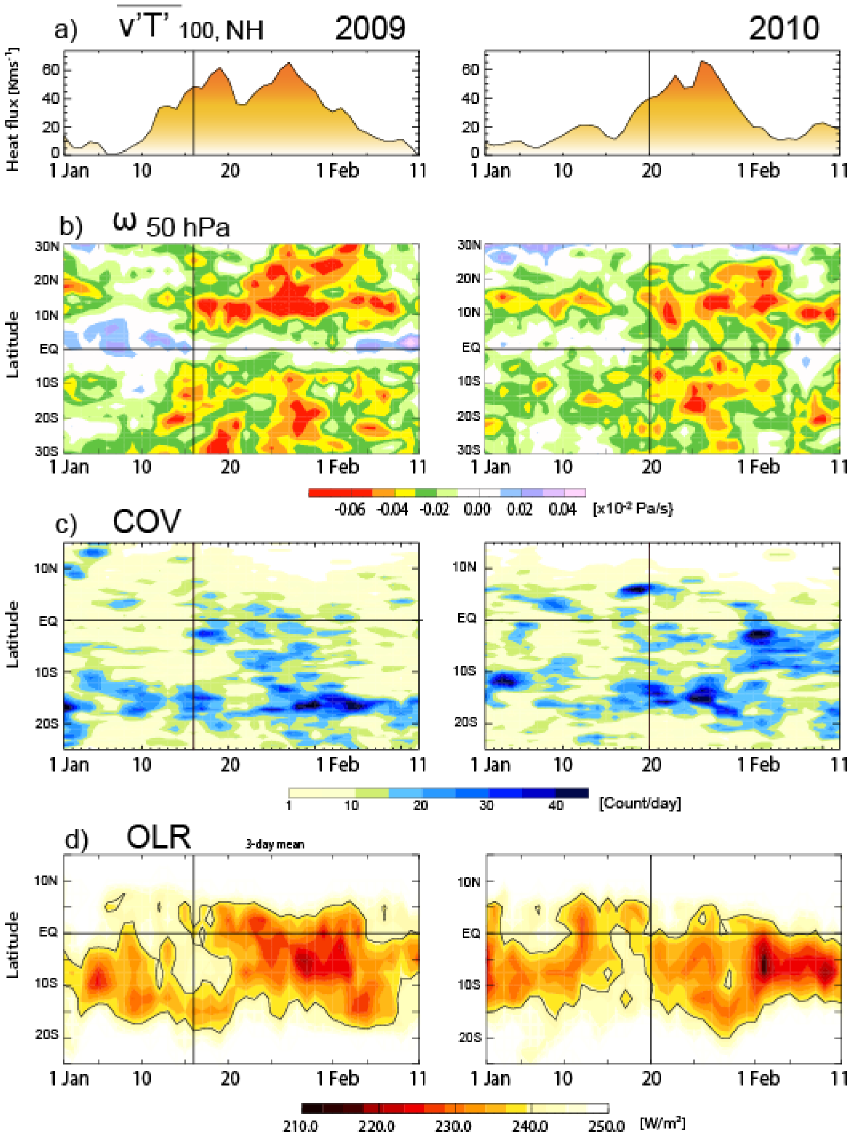
Figure 2. a) Correlation coefficient between the pressure coordinate vertical velocity (ω) at each pressure level and the daily convective overshooting occurrence frequency (COV) averaged over the tropics. b) As for (a), but for deep convection (DC). c) As for (a), but for the correlation coefficient with –OLR. d) Same as in (a), except for COV and temperature at each level. e) Same as in (d) except for COV and vertical temperature gradient at each level, f) Same as in (e) , except for –OLR and vertical temperature gradient. Variables were first averaged over 25°S to 25°N and then the correlation was calculated over 31 days centered at the onset day (16 January in 2009 and 20 January in 2010). Solid and dashed lines indicate 2009 and 2010, respectively.

Figure 3. a)Similar to Fig. 1, except for the pressure–time section of the zonal mean temperature tendency averaged over the SH tropics (20°S to the equator) [K day^{-1}]. b) As for (a), except for the geographical altitude-time section of cloud frequency measured by CALIOP [%]. (c) As for (a), except for the pressure coordinate vertical velocity anomalies normalized by the standard deviation of daily variability. d) Time series of the daily TRMM surface precipitation averaged over SH tropics [mm day^{-1}]. Horizontal solid lines in (a) and (c) and dashed lines in (b) indicate 100 hPa pressure level.

Figure 4. (a, c, e, g): seven-day mean OLR (color shadings) with velocity potential at 925 hPa (contours of 6, and 8 × 10^6 m^2 s^{-1}). (b, d, f, h): seven-day average of the number of COV in each 2.5° lat/lon grid box. (a,b) and (c,d) are seven-day period before (i) and after (ii) the onset of the event in January 2009. (e,f) and (g, h) are the same as (a,b) and (c,d), except for the event in January 2010.

Figure 5 (a) Composite analysis of twelve SSWs during boreal winters from 1979- 2001 (see Kodera (2006) for detail): Low pass filtered zonal-mean zonal wind tendency at 10 hPa averaged over 50°-70°N of twelve events (top). Student-t values of composited vertical pressure velocity averaged over 30°S-30°N in the stratosphere (middle) and that of 10°S-Equator in the troposphere. (b) Zonal-mean zonal wind tendency in winters 2009 and 2010 similar to Figure 7a (top). Normalized tropical vertical pressure velocity averaged over 20°S-Equator in January 2009 (middle) and January 2010 (bottom). Vertical lines indicate key date (see text). Rectangles indicate a period of enhanced tropospheric upwelling in (a).

Figure 6. Time–longitude sections of three-day running mean equatorial (5°S–5°N) OLR over the Indian Ocean–central Pacific sector (30°E–150°W) during boreal winter for (left) 2008/2009 and (right) 2009/2010. The figure displays a two-month period centered on the onset day of the tropical stratospheric upwelling events (16 January 2009 and 20 January 2010) indicated by horizontal solid lines.



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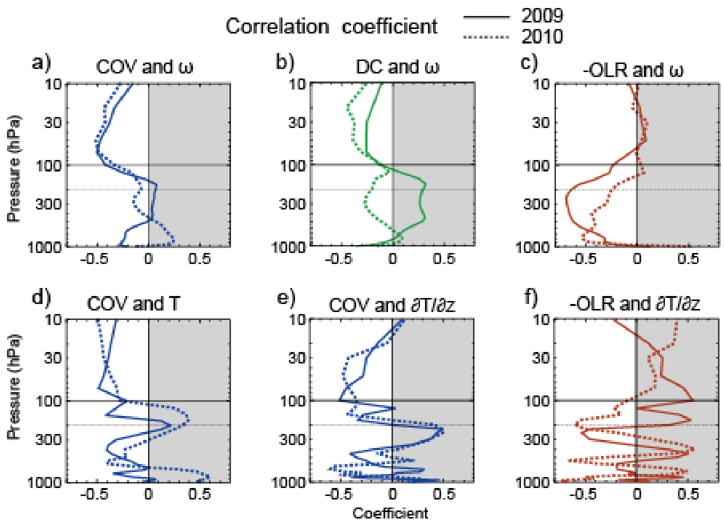

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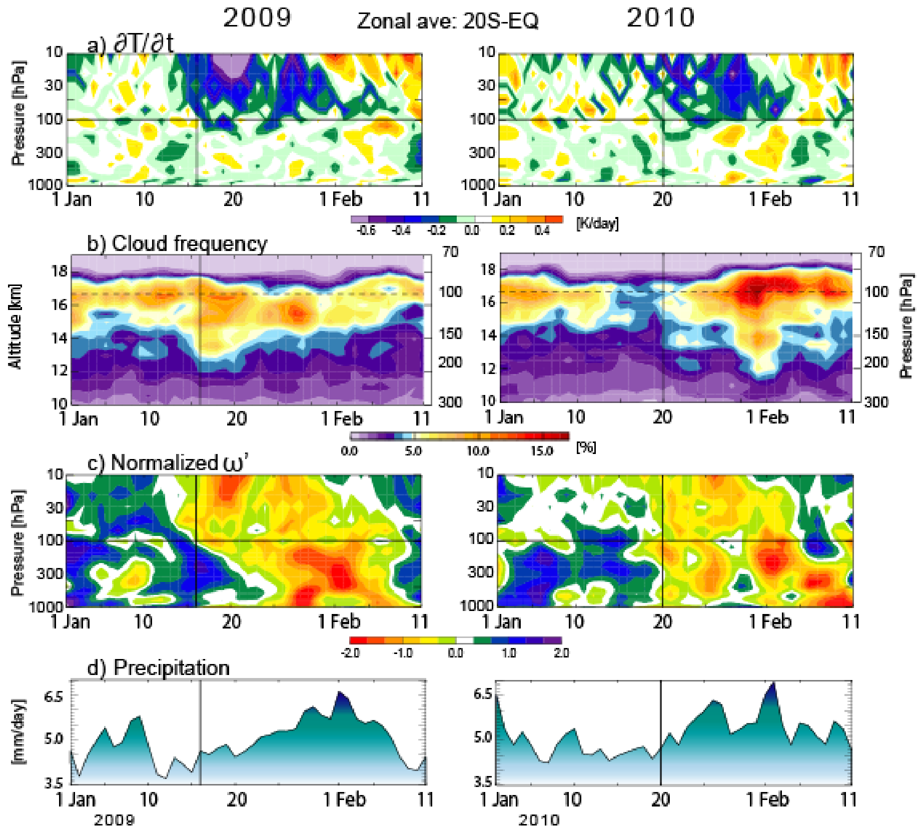

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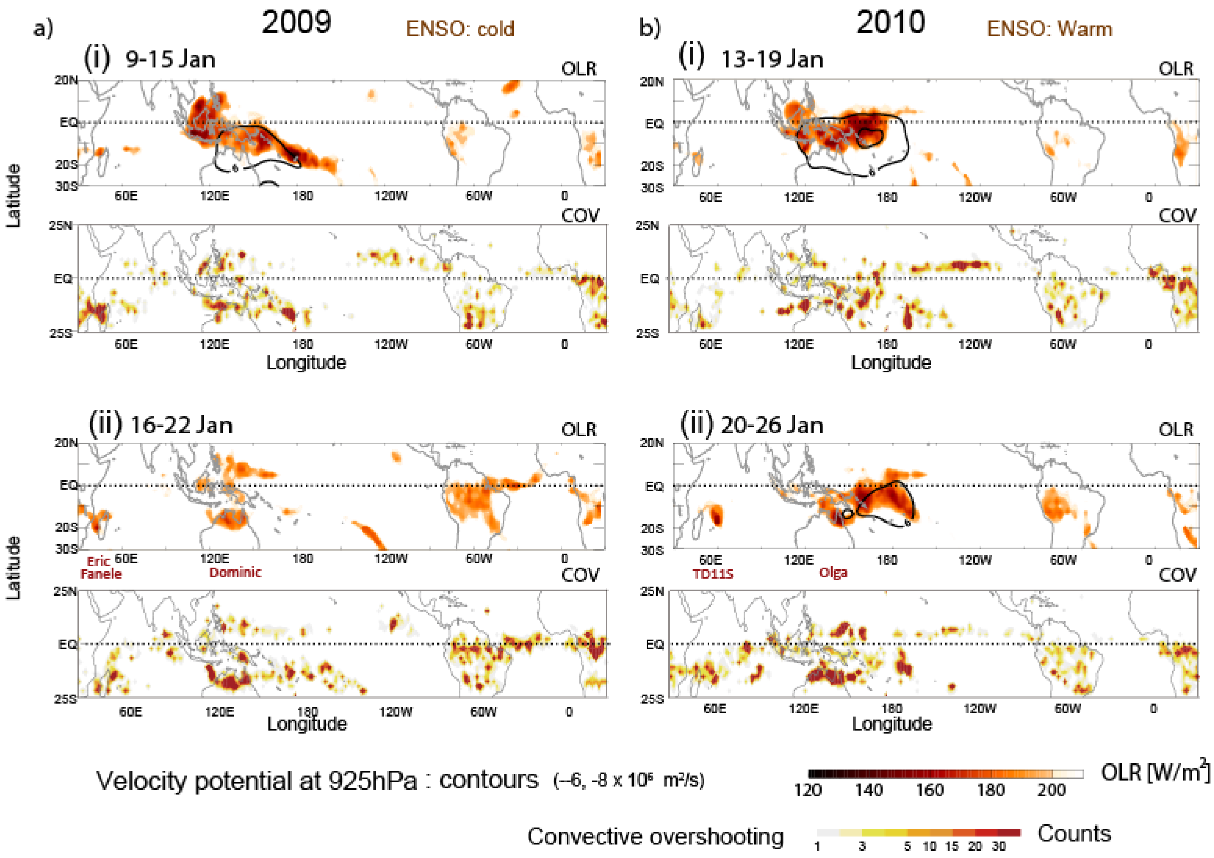

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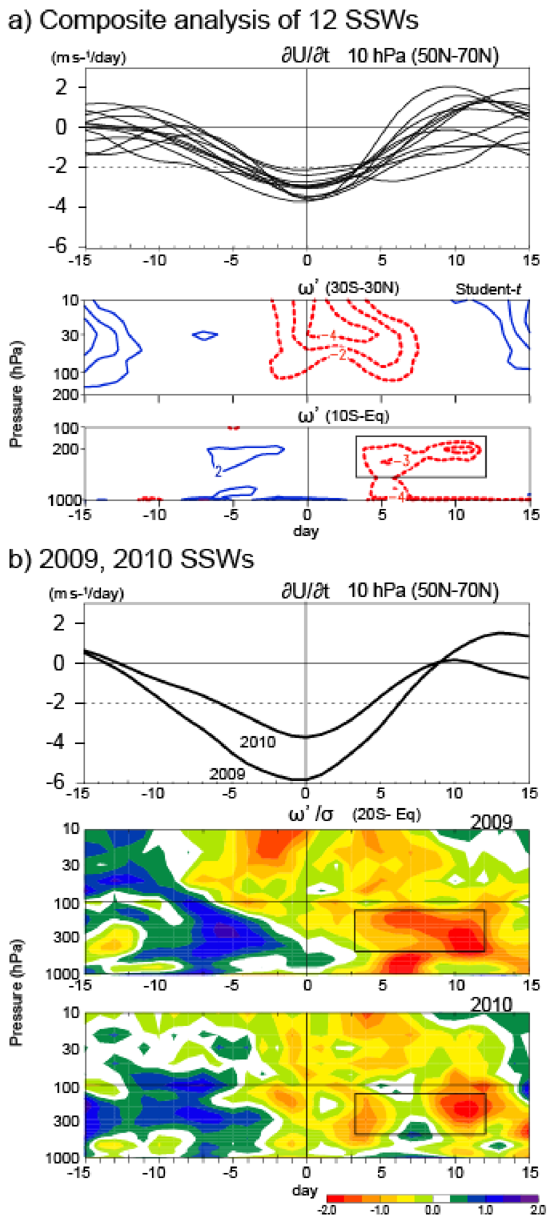

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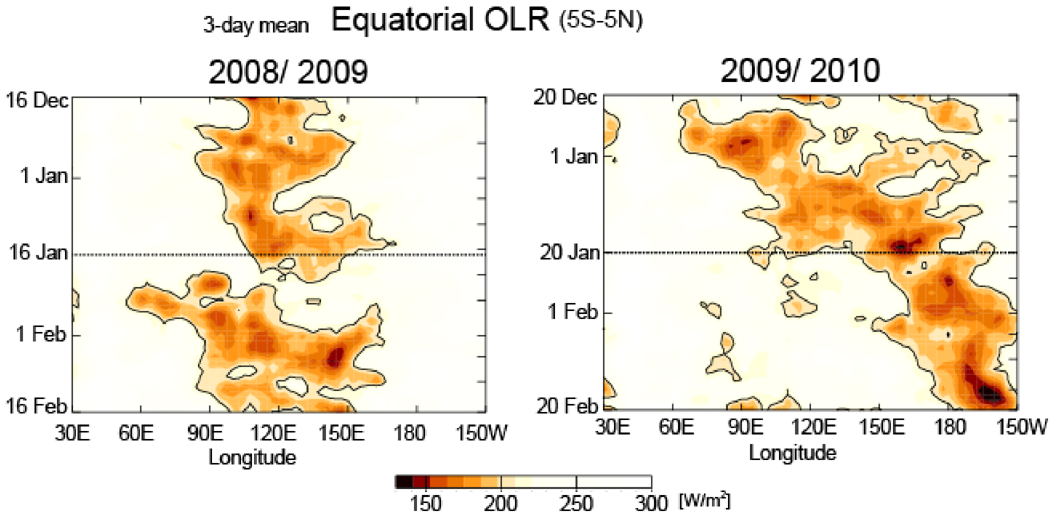

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